ON THE BIRTH MASSES OF THE ANCIENT GLOBULAR CLUSTERS

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ABSTRACT

All globular clusters (GCs) studied to date show evidence for internal (star-to-star) variation in their light element abundances (including Li, C, N, O, F, Na, Mg, Al, and probably He). These variations have been interpreted as evidence for multiple star formation episodes within GCs, with secondary episodes fueled, at least in part, by the ejecta of asymptotic giant branch (AGB) stars from a first generation of stars. A major puzzle emerging from this otherwise plausible scenario is that the fraction of stars associated with the second episode of star formation is observed to be much larger than expected for a standard IMF. The present work investigates this tension by modeling the observed anti-correlation between [Na/Fe] and [O/Fe] for 20 Galactic GCs. If the abundance pattern of the retained AGB ejecta does not depend on GC mass at fixed [Fe/H], then a strong correlation is found between the fraction of current GC stellar mass comprised of pure AGB ejecta, f_p, and GC mass. This fraction varies from 0.20 at low masses ($10^{4.5}$ $M_\odot$) to 0.45 at high masses ($10^{6.5}$ $M_\odot$). The fraction of mass associated with pure AGB ejecta is directly related to the total mass of the cluster at birth; the ratio between the initial and present mass in stars can therefore be derived. Assuming a star formation efficiency of 50%, the observed Na-O anti-correlations imply that GCs were at least $10-20$ times more massive at birth, a conclusion that is in qualitative agreement with previous work. These factors are lower limits because any mass-loss mechanism that removes first and second generation stars equally will leave f_p unchanged. The mass-dependence of f_p probably arises because lower mass GCs are unable to retain all of the AGB ejecta from the first stellar generation. Recent observations of elemental abundances in intermediate-age LMC clusters are re-interpreted and shown to be consistent with this basic scenario. The small scatter in f_p at fixed GC mass argues strongly that the process responsible for the large mass loss is internal to GCs. A satisfactory explanation of these trends is currently lacking.

Subject headings: Galaxy: globular clusters — globular clusters: general

1. INTRODUCTION

Evidence has been accumulating for the past thirty years that globular clusters (GCs) harbor internal (star-to-star) variation in their light element abundances (including Li, C, N, O, F, Na, Mg, and Al; Cohen 1978; Kraft 1979; Smith & Norris 1982b, 1983; Kraft 1994; Gratton et al. 2004; Pasquini et al. 2005; Smith et al. 2005). And yet, save the most massive GCs, they can still be considered mono-metallic in heavier elements including Ca, Si, and Fe (e.g., Carretta et al. 2009a, 2010b).

While early work focused on giant branch stars, abundance variations have now been observed in main sequence turn-off stars (e.g., Gratton et al. 2001; Briley et al. 2002; Cohen et al. 2002; Cannon et al. 1998; Pancino et al. 2010b), and so the observed variations cannot be attributed to non-canonical mixing in evolved stars[1]. Rather, the observed star-to-star variation in elemental abundances must be due to the fact that the stars formed from different material.

Perhaps the most striking result emerging from these observations is that the number of stars within a GC that show anomalous abundance ratios is comparable to those stars that have normal ratios. In this context 'normal' abundance ratios refers to abundances characteristic of field stars at the same [Fe/H] abundance, and 'anomalous' refers to abundance ratios that differ markedly from the field. The comparable number of normal and anomalous stars is observed for all GCs studied to date, spanning a wide range in stellar mass and metallicity (e.g., Martell & Smith 2009; Carretta et al. 2010c).

The anomalous stars display abundance ratios that provide important clues to the source of the raw material from which they formed. These stars show enhanced Na and Al and depleted O and Mg abundances. They are also CN-enhanced and CH-depleted. These peculiar abundance patterns arise naturally when matter is brought to very high temperatures (far exceeding 10^7 K). At sufficiently high temperatures the CNO, Na-Ne, and Mg-Al nuclear reaction cycles are activated (the precise temperature required for activation of these cycles depends in detail on the site, whether e.g., the stellar interior or the at the base of the convective envelope; Charbonnel & Prantzos 2006; Karakas & Lattanzio 2007; Ventura & D'Antona 2008b). In intermediate-mass asymptotic giant branch (AGB) stars, the base of the convective envelope reaches temperatures that are necessary to ignite these nuclear cycles. Because the envelope is convective, material through the whole envelope can therefore participate in nuclear burning. This process is known as envelope, or hot bottom burning, and it occurs for stars of initial masses in the range 4 $M_\odot \lesssim M \lesssim 8$ $M_\odot$ (e.g., Renzini & Voli 1981; Ventura & D'Antona 2008b). Formation of the anomalous abundance ratios within the envelopes of AGB stars is appealing because these stars do not produce heavier elements such as Ca, Si, and Fe, which then explains the lack of observed variation in these elements in most GCs studied to date. These stars also produce large amounts of He, which seems neces-

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[1] Although non-canonical mixing cannot explain the totality of the observed star-to-star variation within GCs, there are well-documented correlations between some elemental abundances, such as carbon and nitrogen, and location along the giant branch (see e.g., Smith 2002) that cannot be explained by state-of-the-art stellar evolutionary models. This fact significantly complicates interpretation of certain elements.

stars observed, incomplete spatial coverage, and the short relaxation times for many GCs.

Parallel to the advances in the chemical abundances of normal GCs has been the revelation of distinct stellar populations in the color-magnitude diagrams (CMDs) of the most massive GCs as revealed by the *Hubble Space Telescope* (see Piotto 2009, for a review). It is now clear that the massive GCs ωCen and NGC 2808 harbor multiple distinct main sequences as seen in their CMDs. Many more GCs harbor distinct sub-giant branches and significant width in their red giant branches. Although it is clear that the spread in the CMDs is related to the elemental abundance variations (Yong et al. 2008; Marino et al. 2008; Carretta et al. 2009c; Milone et al. 2010), a comprehensive understanding of the relation between these two phenomena is currently lacking. In particular, while much attention has been focused on the peculiar CMDs of the most massive GCs, it is far from clear that the features of these GCs are characteristic of the population as a whole.

The present work aims to provide a quantitative understanding of the relative frequencies of first and second generation stars, the amount of material accreted from the ambient ISM, and the amount of AGB ejecta required to explain the observed elemental abundance variations, over a factor of 100 in GC mass. This work therefore aims to bridge our understanding of the properties of lower mass clusters with the most peculiar massive GCs. One of the major goals of the present analysis is to answer the following question: "how much more massive did the progenitors of present day GCs need to be in order to explain the observed abundance variations within GCs?"

2. A SIMPLE MODEL FOR THE ABUNDANCE VARIATIONS

One of the most intriguing observational results is the strong anti-correlation between [Na/Fe] and [O/Fe] within a given cluster. It has been shown in previous work that this anti-correlation can be reproduced with a simple dilution model wherein second generation stars form from normal and processed material mixed in varying amounts (Prantzos et al. 2007; Ventura & D'Antona 2008a, 2009; D'Ercole et al. 2010). Processed material means in this context matter that has been exposed to temperatures exceeding $\approx 7 \times 10^7 K$, where the CNO and Na-Ne nuclear reactions are active in the convective envelopes of massive AGB stars. Stars formed from pure processed material have enhanced [Na/Fe] and depleted [O/Fe] abundances. Normal material means here matter that has the same abundance patterns as the initial stellar population, and also probably has the same abundance patterns as field stars in the Galaxy, at the same [Fe/H]. Normal material at the low metallicities considered has enhanced [O/Fe] and either solar or sub-solar [Na/Fe] abundances. In the present discussion, 'AGB ejecta' will be synonymous with 'pure processed material', as it is assumed herein that the source of the processed material is AGB ejecta.

If the normal and processed abundances are denoted with subscripts 'o' and 'p' and if the fraction of pure processed material in the j−th star is f_p^j then the abundance of element i in a star formed from a mixture of normal and processed material is simply:

$$[i/\mathrm{Fe}]_j = \log\left((1-f_p^j)10^{[i/\mathrm{Fe}]_o} + f_p^j 10^{[i/\mathrm{Fe}]_p}\right), \qquad (1)$$

assuming Fe is constant.

It is important to notice that in the context of this model

there will be stars with $f_p^j = 0.0$; these are truly first generation stars that formed purely from normal material. Subsequent generations of stars then form from a mixture of AGB ejecta and normal material. The source of the normal material required to produce the observed [Na/Fe] and [O/Fe] values in the second generation is currently unknown. A plausible source is accretion from the ambient ISM over the several 10^8 yr when intermediate-mass AGB stars are evolving, and after the type II SNe have exploded and cleared the GC of any remaining initial gas (Conroy & Spergel 2011).

Once the normal and processed abundances of [Na/Fe] and [O/Fe] are specified, one can readily estimate f_p^j for each star in a GC by comparing the star's observed Na and O abundances to the model predictions. An estimate of the global value of f_p can then be obtained by averaging the individual f_p^j values over all the stars in the GC. This global f_p represents the fraction of the present stellar mass comprised of pure AGB ejecta. The fraction of the present GC stellar mass formed from normal material is then given by $1-f_p$.

This procedure for determining f_p is straightforward. An advantage of this approach is that no arbitrary, sharp distinction is made between first and later generations of stellar generations based on their location in the Na-O plane. This is advantageous because the observed distribution of stars along the Na-O anti-correlation is continuous in most GCs, and so there is no natural way to separate first and later generations.

A complication in interpreting the results from such a dilution model is that the fraction of normal material is not easily separable into the normal material comprising the initial stellar population and the normal material locked in second generation stars. This ambiguity arises because stars with $0 < f_p \lesssim 0.1$, which are second generation stars, are confused with stars with $f_p = 0.0$, which are truly first generation stars. The fraction of normal material that is associated with second generation stars will be denoted by $f_{\rm acc}$. The fraction of total mass in the first stellar generation is then $f_1 = (1-f_p)(1-f_{\rm acc})$, and the fraction of total mass in accreted material is $f_a = (1-f_p)f_{\rm acc}$. The fraction of mass in the second generation is then $f_2 = f_a + f_p$.

Ultimately we are interested in knowing if the amount of mass in pure AGB ejecta incorporated in second generation stars and given by Mf_p where M is the total GC stellar mass, can be produced from the first stellar generation. The initial mass needed to produce the observed amount of AGB ejecta can be estimated as follows. First, define $f_{\rm AGB}$ as the fraction of initial mass that ends up in AGB ejecta and is available for second generation star formation. It can be computed from stellar evolution in conjunction with an IMF. Next, define $\epsilon_{\rm SF}$ as the star formation efficiency, or the fraction of gas mass within the young GC that ends up in second generation stars. The initial mass then needed to produce the observed amount of AGB ejecta is $Mf_p/f_{\rm AGB}/\epsilon_{\rm SF}$. The ratio between this quantity and the actual amount of mass in long-lived[2] first generation stars, $M(1-f_p)(1-f_{\rm acc})$, is:

$$f_{M1} = max\left(1.0, \frac{f_p}{\epsilon_{\rm SF}f_{\rm AGB}(1-f_p)(1-f_{\rm acc})}\right). \qquad (2)$$

[2] For a canonical Kroupa (2001) IMF, approximately 50% of the initial stellar mass of a population is lost due to stellar evolution and death. In the present analysis attention is focused on *long-lived stars*, so the massive stars that carry away substantial mass when they die are not included in bookkeeping except where explicitly mentioned.

Table 1
Summary of Symbols and Quantities

	Derived From	Description
f_p	Na-O dilution model	fraction of GC mass comprised of AGB ejecta
f_{acc}	free parameter	fraction of normal material accreted from ambient ISM
f_{AGB}	stellar evolution, IMF	fraction of mass in AGB ejecta from a coeval stellar population
ϵ_{SF}	free parameter	efficiency of star formation
f_a	$(1-f_p)f_{acc}$	fraction of GC mass in accreted material
f_1	$(1-f_p)(1-f_{acc})$	fraction of GC mass in first generation stars
f_2	$f_a + f_p = 1 - f_1$	fraction of GC mass in second generation stars
f_{M1}	Equation 2	mass enhancement factor for first generation
f_t	Equation 3	total mass enhancement factor

The quantity, f_{M1} is the mass enhancement factor for the first generation, considering only long-lived stars. If stars of all masses are included then f_{M1} should be increased by a factor of ≈ 2 (see footnote 2). The definition of f_{M1} in Equation 2 preserves the requirement that f_{M1} cannot be less than unity. It is instructive to consider a quantitative example. If $f_{AGB} \approx 0.1$ (as suggested by stellar evolution and a canonical Kroupa (2001) IMF), $f_p = 0.5$, $f_{acc} = 0.5$, and $\epsilon_{SF} = 0.5$, then $f_{M1} = 40.0$. This means that the first generation contained $40\times$ more long-lived stars at birth compared to its present mass.

In what follows a star formation efficiency of $\epsilon_{SF} = 0.5$ will be adopted. The simplest argument for a high star formation efficiency in GCs is based on the Virial Theorem and the requirement that GCs remain gravitationally bound. This argument suggests that the total mass in stars formed needs to be at least 50% of the initial gas mass (the resulting bound mass depends on how quickly gas is removed from the system, for details see Lada et al. 1984). The gas available for second generation star formation finds itself in a unique configuration in that it is at the bottom of a deep potential well (set by the first generation stars). In principle the star formation efficiency could therefore be lower and yet still result in a bound cluster. The uncertainty carried by the parameter ϵ_{SF} is an inevitability of the present analysis.

While recognizing that in reality star formation is not 100% efficient, previous work has nonetheless made the assumption that 100% of AGB ejecta from the first generation is incorporated into second generation stars. This assumption was made for the simple reason that it minimizes the required mass enhancement factor. In the present work a more realistic value for ϵ_{SF} has been adopted.

Another quantity of interest is the *total* mass enhancement factor in long-lived stars, that is, the ratio of total mass at birth to total present mass. This quantity is

$$f_t = max\left(1.0, \frac{f_p}{\epsilon_{SF} f_{AGB}}\right). \qquad (3)$$

Notice that this is smaller than f_{M1} by a factor of $(1-f_p)(1-f_{acc})$ for $f_t > 1$. In the example above, the total mass enhancement factor would be 10, a factor of four smaller than the mass enhancement factor for the first generation. The former is smaller than the latter because of the addition of second generation stars, which at least partially compensates for the substantial loss of first generation stars. For reference, a GC evolving in isolation that experiences no secondary generations of star formation and also experiences no loss of stars from e.g., stellar evaporation or ejection, will have $f_{M1} = 1$ and $f_t = 1$.

Most authors assume that second generation stars are born with masses in the range $0.1 - 0.8\ M_\odot$ (e.g., D'Ercole et al. 2008; Lind et al. 2011). This assumption is made in order to minimize the required mass enhancement factors. If AGB ejecta is only placed in long-lived second generation stars, then none of the ejecta is 'wasted' on higher mass stars that evolve and die on short timescales. This assumption reduces the required mass enhancement by a factor of ≈ 2 compared to the assumption, made in the present work, that second generation stars fully populate a standard Kroupa (2001) IMF. A fully populated IMF is assumed here because there is no physical reason to believe that the IMF should be biased toward low masses during second generation star formation.

An argument often made for an IMF of second generation stars that is skewed toward low masses is that massive second generation stars would explode and thereby truncate further star formation. This is certainly an issue that must be addressed in any comprehensive theory, but it is not a strong argument for a skewed IMF. As discussed in Conroy & Spergel (2011), the heating rate of UV photons should be substantial during the first $\sim 10^8$ yr of the young GC. This heating may be sufficient to delay star formation until the UV photon production rate drops precipitously at $\sim 10^8$ yr. After this time, the gas may cool catastrophically in a manner analogous to the formation of the first generation of GC stars. This simple scenario suggests that massive second generation stars could form and yet not have a debilitating effect on the conversion of a significant fraction of the accumulated gas into stars.

The symbols and quantities defined in this section are summarized in Table 1 for convenience.

3. CONSTRAINTS ON THE BIRTH MASSES OF GALACTIC GCS

Recently, Carretta and collaborators have published abundance measurements for > 1800 red giant stars in 20 GCs spanning a wide range in mass and metallicity (Carretta 2006; Carretta et al. 2007a, 2009c, 2010d). The abundances were derived from high resolution spectra obtained with the FLAMES spectrograph at the VLT. Basic data for this sample are collected in Table 2, including common names, average [Fe/H] values, and number of stars with abundance determinations or upper limits for both [O/Fe] and [Na/Fe]. Stellar masses are derived from luminosities adopted from the Harris (1996) catalog assuming $M/L_V = 2\ M_\odot/L_\odot$. The table also includes a variety of derived products discussed in detail below, including the inferred [Na/Fe] and [O/Fe] abundances of both processed and normal material, the fraction of processed material (AGB ejecta), the average distance of the stars observed to the cluster center in units of the half-mass radius (the latter adopted from the Harris catalog), and the mass enhancement factors.

Stars were used in the following analysis only if they have reported abundance measurements or upper limits for both [Na/Fe] and [O/Fe]. Some stars were observed in a configuration that did not include the spectral region covering the [OI] line; such stars are not included in the analysis below. The decision of whether or not to include the [OI] line is not correlated with the actual [O/Fe] abundance, so removing such objects should not affect the results.

The model [Na/Fe] and [O/Fe] abundances of the normal and processed material for each cluster were estimated by eye from the distribution of stars in the [Na/Fe]-[O/Fe] plane. The estimated abundances of the normal material lie within the range of the abundances of field stars at the same [Fe/H] (Venn et al. 2004; Carretta et al. 2010c).

Table 2
Summary of GC Data

ID		[Fe/H] (1)	N (2)	log(M) (3)	[Na/Fe]$_o$ (4)	[O/Fe]$_o$ (5)	[Na/Fe]$_p$ (6)	[O/Fe]$_p$ (7)	f_p (8)	$\langle R \rangle / R_h$ (9)	f_{M1} (10)	f_t (11)
NGC 7099	M30	-2.33	19	5.19	-0.30	0.50	0.80	-0.80	0.32	2.33	18.7	6.37
NGC 7078	M15	-2.33	20	5.89	-0.30	0.50	0.80	-0.80	0.36	1.47	22.4	7.19
NGC 4590	M68	-2.23	36	5.16	-0.35	0.60	0.80	-0.80	0.28	1.83	15.2	5.52
NGC 6397		-1.98	13	4.87	-0.30	0.40	0.80	-0.80	0.20	1.04	10.1	4.04
NGC 6809	M55	-1.98	75	5.24	-0.25	0.45	0.80	-0.80	0.33	1.14	19.9	6.65
NGC 6715	M54	-1.57	76	6.23	-0.15	0.40	0.80	-0.80	0.42	3.65	29.5	8.49
NGC 1904	M79	-1.55	39	5.37	-0.25	0.30	0.80	-0.80	0.31	1.92	17.9	6.18
NGC 6752		-1.56	88	5.31	-0.10	0.50	0.80	-0.80	0.36	1.69	22.1	7.12
NGC 6254	M10	-1.56	77	5.21	-0.40	0.40	0.70	-0.80	0.27	1.54	14.9	5.44
NGC 3201		-1.50	94	5.21	-0.30	0.30	0.60	-0.80	0.34	1.12	20.2	6.72
NGC 5904	M5	-1.34	106	5.75	-0.20	0.45	0.70	-0.80	0.38	1.73	24.5	7.59
NGC 6218	M12	-1.31	66	5.15	-0.20	0.50	0.80	-0.80	0.34	1.62	20.9	6.87
NGC 288		-1.23	64	4.92	-0.10	0.25	0.80	-0.80	0.29	1.35	16.5	5.83
NGC 6121	M4	-1.20	80	5.10	-0.10	0.40	0.80	-0.80	0.33	0.88	19.3	6.52
NGC 6171	M107	-1.06	27	5.07	0.00	0.40	0.80	-0.80	0.31	2.01	17.7	6.14
NGC 2808		-1.10	90	5.98	-0.10	0.40	0.60	-0.80	0.42	3.14	29.0	8.40
NGC 6838	M71	-0.80	31	4.46	0.00	0.50	0.80	-0.80	0.25	0.93	13.3	4.98
NGC 104	47 Tuc	-0.74	109	5.99	0.10	0.35	0.75	-0.80	0.40	1.66	27.2	8.10
NGC 6388		-0.40	29	5.99	0.00	0.20	0.70	-0.80	0.39	5.56	26.1	7.90
NGC 6441		-0.34	24	6.08	-0.10	0.20	0.70	-0.80	0.36	9.16	23.0	7.30

Note. — (1): average GC [Fe/H] abundance; (2): number of stars used in the analysis; (3): logarithm of GC stellar mass in units of $M_\odot$; (4): [Na/Fe] abundance of normal material; (5): [O/Fe] abundance of normal material; (6): [Na/Fe] abundance of pure processed material; (7): [O/Fe] abundance of pure processed material; (8): AGB ejecta mass fraction; (9): average cluster-centric radius of stars in units of the cluster half-mass radius; (10): first generation mass enhancement factor; (11): total mass enhancement factor.

The distribution of [Na/Fe] and [O/Fe] abundances is shown for all 20 GCs in Figure 1, along with the corresponding dilution models. The typical error on the [Na/Fe] and [O/Fe] abundances is 0.08 and 0.14 dex, respectively (Carretta et al. 2009c). These errors are dominated by uncertainties in the measured equivalent widths, but also include error due to the adopted atmospheric parameters. The GCs are sorted by increasing stellar mass. It is apparent that the lower mass GCs have on average shorter Na-O anti-correlations than the higher mass clusters, a trend that has been noticed before (e.g., Carretta et al. 2007b, 2010c). This trend, readily apparent in the data, will be the ultimate source of the GC mass-dependent trends discussed below.

3.1. Derivation of f_p for Galactic GCs

By comparing the abundance patterns of stars within each GC to the corresponding dilution model, f_p^j for each star and hence the average f_p for the cluster can be estimated[3]. The result is shown as a function of GC stellar mass in Figure 2. The parameter f_p is only weakly sensitive to the adopted abundances of the pure processed and normal material in the dilution model, as discussed below. Errors on f_p have been estimated in the following way. New dilution models were run for each GC with variation in [O/Fe]$_p$ by ± 0.4, [Na/Fe]$_p$ by ± 0.1, [O/Fe]$_o$ by ± 0.05, and [Na/Fe]$_o$ by ± 0.1, and the resulting minimum and maximum f_p values from this procedure were adopted as the standard error. The range adopted for each parameter was determined by the typical variation allowed by the data. The [Na/Fe]$_p$ abundance is relatively well-constrained by the data, especially for GCs with stars both above and below the knee in the model. The choice of [O/Fe]$_p$ has only a modest effect on f_p because of the nature

of the dilution model - stars on the upper branch of the Na-O correlation can have very different [O/Fe] values and yet very similar f_p^j.

There is a strong correlation between GC mass and the fraction of mass comprised of pure AGB ejecta. The correlation is particularly strong when restricted to GCs with [Fe/H] > -1.5. This correlation is a quantitative manifestation of the trend noted above that low mass GCs have short Na-O anti-correlations compared to high mass GCs. The best-fit relation between f_p and GC mass is:

$$f_p = (0.10 \pm 0.021) \log(M/M_\odot) - (0.21 \pm 0.12). \quad (4)$$

There are only two GCs at the low mass end, and one might wonder to what extent they are influencing the observed correlation. If those two clusters are removed, the significance of the correlation is reduced from 4.8σ to 3.1σ; the trend is therefore robust to the removal of the two lowest mass clusters in the sample.

As discussed in the Introduction, there is some evidence that the extent of the Na-O anti-correlation is a function of radius within GCs. One might then wonder if the trend seen in Figure 2 is due to a selection effect. In order to test for such an effect, for each GC the average radius of stars for which abundance data are available was computed in units of the GC half-mass radius. The results are tabulated in Table 2 and shown as a function of GC mass in Figure 3. The lowest-mass GC and the four GCs with $\langle R \rangle / R_h > 3$ define a weak trend with mass. If these five GCs are excluded, there is no remaining trend with mass in Figure 3, and yet the strong correlation between f_p and mass remains. Future observations over a greater range in radius would be valuable, but even with current data it is clear that the trend of f_p with mass is not due to sampling systematically different regions of GCs as a function of their mass.

As can be seen in Table 2, the adopted pure AGB ejecta abundances [O/Fe]$_p$ and [Na/Fe]$_p$ vary only weakly, or not at

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[3] For stars with upper limits on [O/Fe] abundances, only the [Na/Fe] values were used to determine f_p^j. Other choices for how to handle upper limits do not change the overall results.
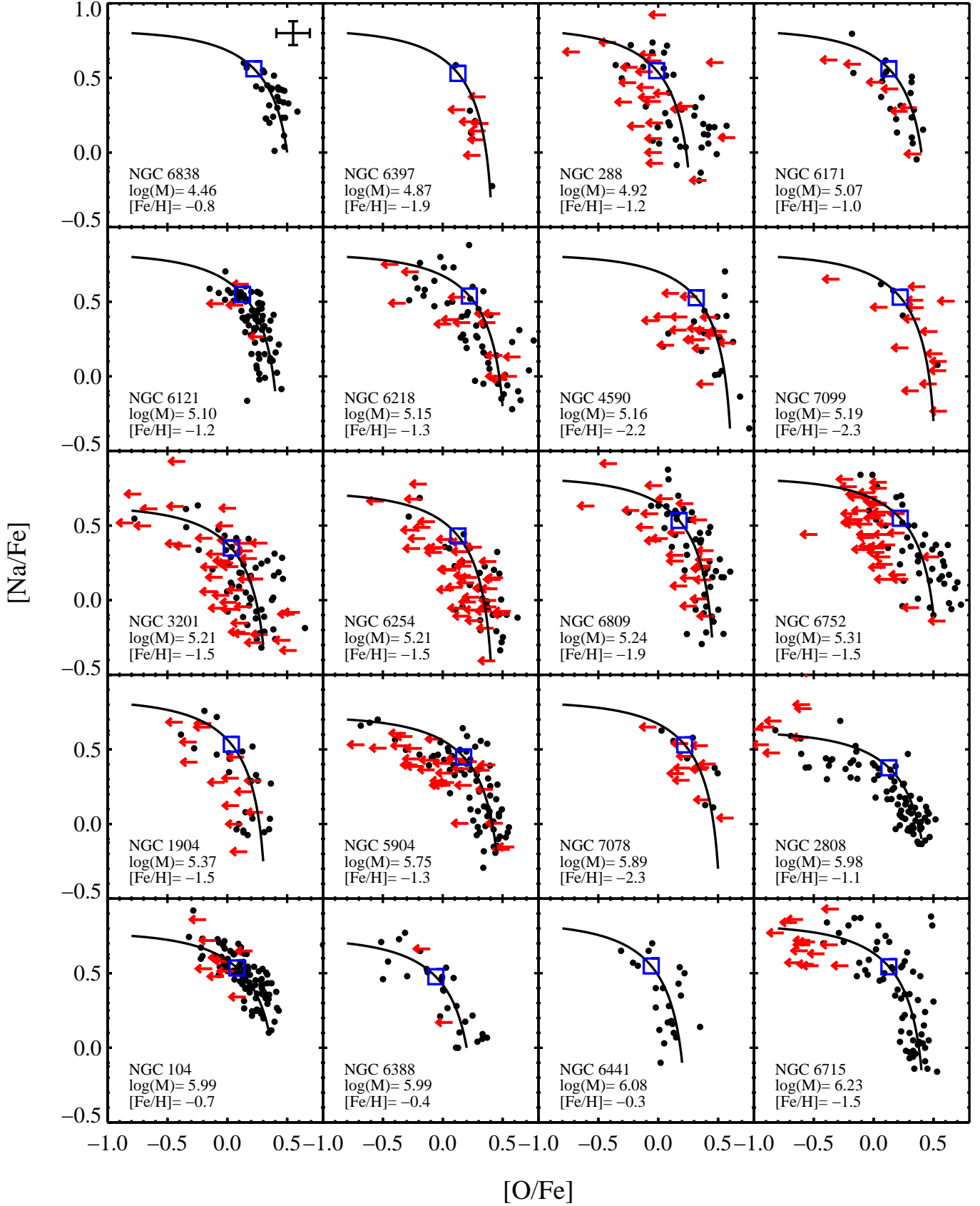
Figure 1. Na–O anti-correlation for 20 GCs. Data are from Carretta (2006), Gratton et al. (2007), and Carretta et al. (2007a,c, 2009c,b, 2010d). GCs are sorted by mass, and the logarithm of the GC stellar mass in solar units is shown in each legend, as is the average [Fe/H] of each cluster. Arrows indicate upper limits on [O/Fe] abundances. A typical error on the abundances is shown in the upper left panel. Lines show the dilution models, and open squares mark the location at which the contribution from AGB ejecta and normal material is equal.
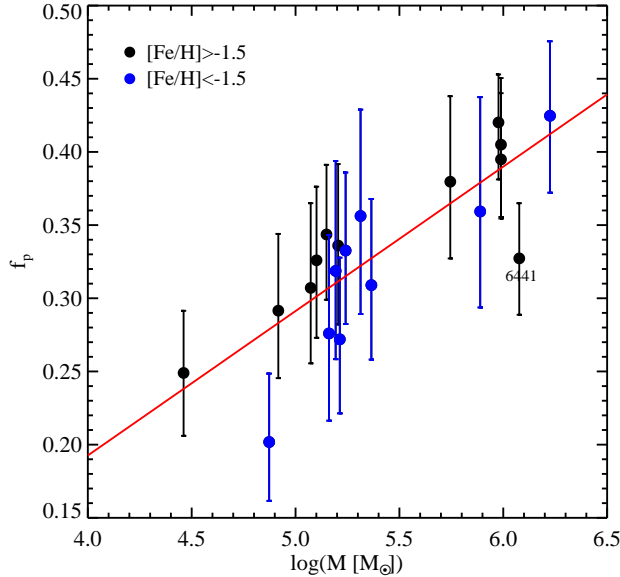
Figure 2. Relation between the fraction of GC mass comprised of AGB ejecta, f_p, and GC stellar mass. GCs are color-coded according to their metallicity. The solid line is the best-fit linear relation. The metal-rich bulge GC NGC 6441 is labeled.

Figure 3. Average cluster-centric radius of stars for which abundance measurements are available, in units of the GC half-mass radius. Results are shown for all 20 GC as a function of GC mass. There is no strong trend with GC mass, which implies that the results in Figure 2 are not biased by observing clusters of different masses at different average radii. The metal-rich bulge GC NGC 6441 is labeled as it is a significant outlier.

all, with GC mass and [Fe/H]. The abundances were chosen to be $[O/Fe]_p = -0.8$ and $[Na/Fe]_p = 0.8$ initially, and only changed if demanded by the data. The adopted abundances for each GC are not unique, and for the GCs with the shortest Na-O anti-correlations, there is a substantial amount of room for variation.

The pure processed abundances could have been adopted from the latest AGB yields of Ventura & D'Antona (2009), but, as noted by those authors and others (e.g., Ventura & Marigo 2010), the yields are quite uncertain, especially for Na and O, and do not provide good fits to the observed abundances of anomalous stars. For example, D'Ercole et al. (2012) were able to model the very low [O/Fe] abundances in NGC 2808 only after invoking an additional deep-mixing mechanism in red giants to lower the [O/Fe] abundances below the standard AGB yields. It is clear that AGB models still cannot, from first principles, produce elemental yields that match even the *range* of observed abundances in the second generation of stars in GCs. It is for this reason that the model AGB yields were not adopted when choosing $[O/Fe]_p$ and $[Na/Fe]_p$.

The pure AGB ejecta abundance ratios could also have been chosen for each GC to coincide with the most anomalous observed stars in each cluster. This would result in an increase in f_p for each cluster. Consider for example NGC 6838, which as can be seen in Figure 1, contains a short Na-O anti-correlation. If the pure AGB ejecta abundances were chosen to be $[O/Fe]_p = 0.0$ and $[Na/Fe]= 0.6$, then the resulting pure processed fraction would be $f_p = 0.4$ rather than $f = 0.25$. Doing this for each GC would yield a pure processed fraction, f_p that was essentially independent of GC mass.

However, there is no known reason why the processed yields should be a function of GC mass at fixed [Fe/H]. Compare for example NGC 2808 with NGC 6171. These GCs differ by a factor of ten in mass but have nearly the same [Fe/H]. The adopted pure processed abundances in NGC 6171 can be justified based on the fact that the same abundances fit

the whole extent of the Na-O anti-correlation in NGC 2808. Comparing other GC pairs with similar metallicities, such as NGC 6838 and NGC 104, NGC 6397 and NGC 6809, or NGC 6218 and NGC 5904, provides additional justification for the adopted pure processed yields.

In summary, the derived pure AGB ejecta fractions, f_p, and especially the trends with GC mass, are robust to the details of the model, but they do depend on the assumption that the AGB yields are independent of GC mass at fixed [Fe/H].

3.2. Characterization of the Multiple Stellar Population Phenomenon in Galactic GCs

The relation between f_p and GC mass derived in the previous section can now be used to derive all of the other quantities described in Table 1, once the parameters ϵ_{SF}, f_{acc} and f_{AGB} are specified. Standard stellar evolution in conjunction with a Kroupa (2001) IMF suggests $f_{AGB} \approx 0.1$ for AGB stars in the $3-8\ M_\odot$ range, assuming that all of the AGB ejecta is later available for second generation star formation. Variation of this parameter and f_{acc} will be discussed below. A star formation efficiency of $\epsilon_{SF} = 0.5$ is also adopted.

Relations between various derived properties and present GC mass are shown in Figure 4. Properties include the fraction of present GC mass in pure processed material, f_p, in accreted material, f_a, in first generation stars, f_1, in the second stellar generation, f_2, and mass enhancement factor of stars in the first generation, f_{M1}, and total mass enhancement factor, f_t.

The left panel shows results assuming constant values for f_{AGB} and f_{acc}. The right panel shows how the results change when these two parameters are allowed to be mass-dependent. The mass-dependence of these parameters was chosen so as to produce approximate mass-independence of the derived functions f_{M1}, f_t, f_2, and f_1. The variation in results between the left and right panels serves to illustrate the approximate range
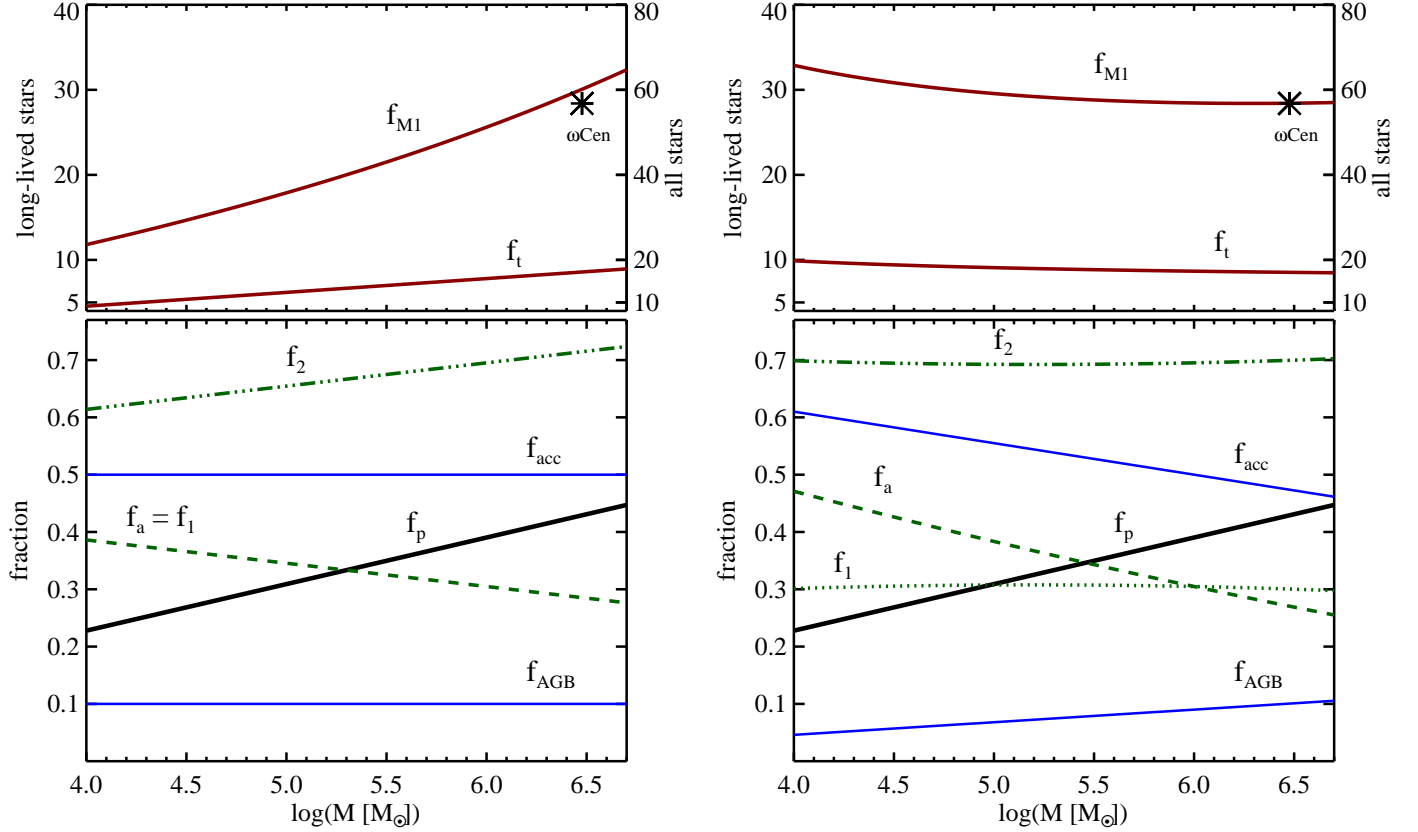
Figure 4. Characterization of the multiple stellar population phenomenon in GCs. Properties shown include the fraction of present GC mass in pure AGB ejecta, f_p, in accreted material, f_a, in first generation stars, f_1, in the second stellar generation, $f_2 = f_p + f_a$, fraction of second generation mass comprised of pristine accreted material, f_{acc}, fraction of initial mass that ends up in AGB ejecta and is available for second generation star formation, f_{AGB}, mass enhancement factor in the first generation, f_{M1}, and total mass enhancement factor, f_t. A star formation efficiency of $\epsilon_{SF} = 0.5$ is assumed. The thick black line is derived from the observations (see Figure 2), the blue lines are assumptions, and the red and green lines follow directly from ϵ_{SF}, f_{AGB}, f_{acc}, and f_p. In the upper portion of the figures, the y–axis on the left side describes the enhancement factors of long-lived stars, while the right side describes the enhancement including all stars. The approximate location of f_{M1} for ωCen is indicated. *Left panel*: The parameters f_{AGB} and f_{acc} are assumed to be constant. *Right panel:* The mass-dependence of the parameters f_{AGB} and f_{acc} are chosen such that the majority of the other derived functions are independent of mass.

in these parameters allowed by the data given the model uncertainties.

It is entirely plausible that both f_{AGB} and f_{acc} are in reality mass-dependent. For example, if Bondi accretion is the physical process responsible for bringing in the accreted material, then f_{acc} should increase with mass, while if simple geometric cross sectional sweeping were dominant, then it may decrease with increasing GC mass (see e.g., Conroy & Spergel 2011). The parameter f_{AGB} represents the fraction of stellar mass that is returned to the ISM as AGB ejecta and available for second generation star formation. If an increasing fraction of AGB ejecta is lost from the young cluster at lower GC masses, then f_{AGB} could decrease with decreasing mass. Such a scenario seems plausible since the wind velocity from AGB stars is in the range $10-20\,\mathrm{km\,s^{-1}}$ (Loup et al. 1993; Vassiliadis & Wood 1993), which is of order the escape velocity for low mass GCs.

The approximate value of f_{M1} is shown for ωCen, and is estimated as follows. Renzini (2008) estimates that 0.7% of the initial mass of a stellar population would be returned to the ISM as *fresh* He (i.e., He produced within stars, as opposed to primordial He) from AGB stars with $3 < M < 8\,M_\odot$. In ωCen, approximately 57% of the stars belong to the metal-poor component, 33% to the intermediate-metallicity component, and

10% to the metal-rich component (Piotto et al. 2005). The CMD morphology of these components suggests He mass fractions of $Y = 0.25$, $Y \approx 0.38$, and $Y \sim 0.4$; the latter value is highly uncertain (Sollima et al. 2005). Taken together, this implies a total mass in fresh He of $\approx 1.7 \times 10^5\,M_\odot$ in long-lived stars. If the metal-poor population represents the first generation, then it could have produced only $1.2 \times 10^4\,M_\odot$ of fresh He, assuming a total mass in long-lived stars of $3 \times 10^6\,M_\odot$ for ωCen. Assuming $\epsilon_{SF} = 0.5$, the mass enhancement factor for the first generation is therefore $f_{M1} = 28$. This independent estimate of f_{M1} agrees fairly well with the value expected for its mass based on extrapolation of the model presented herein.

Several generic features stand out in Figure 4. First, the fraction of second generation stars is always $> 50\%$, and is only a weak function of mass (see also Carretta et al. 2010c). While f_2 is relatively constant, the composition of the second generation stars (given by f_p and f_a) varies more strongly with mass, with the most massive GCs harboring second generation stars comprised largely of pure AGB ejecta, and lower mass GCs containing second generation stars comprised mostly of normal material accreted from the ambient ISM. This is a natural consequence of the fact that lower mass GCs have shorter Na-O anti-correlations compared to higher

mass GCs.

Second, the mass enhancement factor for first generation stars is very large, approximately 30 for the most massive clusters, and at least 10 for the less massive ones. The total mass enhancement factor, f_t, is also quite large, though by factors of $2-3$ smaller than f_{M1}. Previous work drew attention to the fact that f_{M1} has to be large in order to explain the observed abundance patterns, and therefore concluded that GCs must have been substantially larger at birth compared to their present masses. But this is only true with regards to the first generation population. Since the first generation is subdominant by number at the present epoch, the ratio of total mass at birth to the total present mass is factors of several smaller than f_{M1}.

In the present analysis attention has been focused on the mass enhancement factors for *long-lived* stars. However, short-lived stars (defined as stars with ages less than the present age of the Universe) comprise roughly one half of the total initial mass in a coeval stellar population formed from a Kroupa (2001) IMF. The mass enhancement factors for *all* stars are therefore a factor of approximately two larger than that quoted for long-lived stars only. For the most massive clusters, the total mass enhancement factors for all stars are therefore ≈ 20.

It is important to recognize that these mass enhancement factors are all strictly *lower limits* because any mass-loss mechanism that affects both first and second generation populations equally will not affect the distribution of stars in the Na-O plane, which is the fundamental observable underpinning the present discussion. For example, lower mass clusters (several $10^5 \ M_\odot$) can lose a significant fraction of their mass via stellar evaporation over a Hubble time (Fall & Zhang 2001).

The basic conclusion from this section is that the ancient Galactic GCs had to be at least $10-20$ times more massive at birth in order to produce enough AGB ejecta to account for the observed distribution of [Na/Fe] and [O/Fe] abundances.

Finally, the ratio f_p/f_2 quantifies the fraction of mass in second generation stars comprised of pure AGB ejecta. This ratio is $30\%-60\%$ over the full range in GC mass. Broadly speaking, second generation stars are comprised of half pure AGB ejecta and half pristine material, in agreement with previous modeling of the elemental abundance variations within GCs (D'Ercole et al. 2010).

4. ELEMENTAL ABUNDANCE VARIATIONS IN LMC CLUSTERS

Knowledge of the abundance variations in star clusters outside the Galaxy is limited because of the substantial distances to even our nearest neighbors harboring clusters, the Magellanic Clouds. Recently, Mucciarelli et al. (2009) measured Na and O abundances for 18 giants in three old metal-poor GCs in the LMC. They found clear evidence for an Na-O anti-correlation in these clusters that looks broadly similar to the Na-O anti-correlations observed in Galactic GCs.

However, Mucciarelli et al. (2008) measured elemental abundances in 27 red giant stars located within four intermediate-age ($1-2$ Gyr), moderate-metallicity LMC clusters, and concluded that the abundance patterns "show negligible star-to-star scatter within each cluster". Recall that these and other intermediate-age LMC clusters show evidence in their main sequence turn-off points for an internal age spread of several 10^8 yr (Goudfrooij et al. 2009; Milone et al. 2009). These results have been interpreted by Bekki (2011) as evidence for a qualitatively different scenario at work in
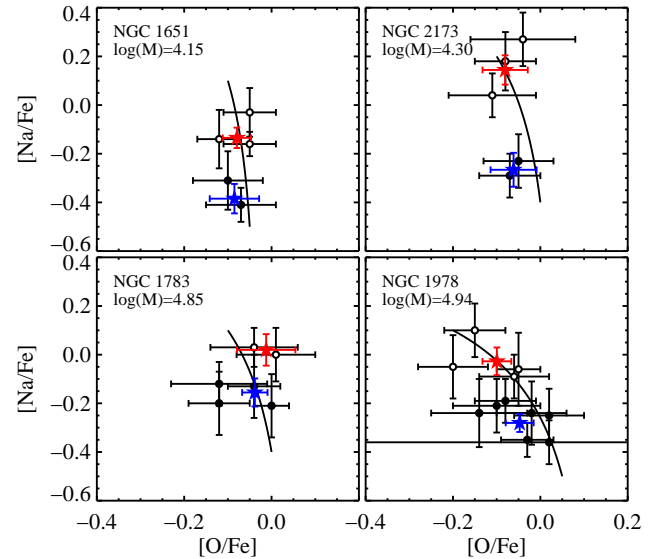

Figure 5. Na-O anti-correlations for intermediate-age LMC clusters sorted by cluster mass. Data are from Mucciarelli et al. (2008). Stellar masses are estimated as described in the text and are shown in the legends in solar units. Dilution models are shown as lines. For each cluster, the data are subdivided by the mean sodium abundance. The mean abundance pattern for each subpopulation is shown as stars.

these clusters (wherein these clusters capture giant molecular clouds that provide the fuel for secondary star formation, without AGB ejecta). It would be much more appealing, on the principle of simplicity, if the multiple stellar population phenomenon observed in these intermediate-age LMC clusters were similar to what is conjectured to have occurred in the ancient Galactic and LMC GCs. A thorough understanding of these clusters is also essential if one hopes to observe present-day young clusters in the process of forming second generation stars.

Motivated by these considerations, the abundance data presented in Mucciarelli et al. (2008) are reinterpreted in the context of the dilution models presented herein. Figure 5 shows the Na-O anti-correlations for the four intermediate-age LMC clusters. Each cluster has an average [Fe/H] abundance of -0.3 to -0.5, which, for solar abundance ratios, corresponds to $Z = 6 \times 10^{-3} - 1 \times 10^{-2}$. The stellar masses of these clusters are estimated by adopting $V-$band magnitudes from van den Bergh (1981), an average $E(B-V) = 0.08$, and a distance modulus of 18.5. A $V-$band mass-to-light ratio of 0.4 was adopted, which is appropriate for a stellar age of 1.6 Gyr and $Z = 6 \times 10^{-3}$.

The stars within each cluster have been split into two groups according to the mean sodium abundance of the stars. The mean sodium and oxygen abundances were then computed within each subpopulation. In all clusters there is statistically-significant evidence for different mean sodium abundances in the two populations. The two populations are most visually striking in NGC 2173 and NGC 1978. Of course, computing the mean abundance of subpopulations split according to that abundance will tend to exaggerate the differences between the two populations. Another way of assessing the statistical significance of the internal sodium variation is to consider the stars at the extremes of the distribution. In NGC 1783 the

stars with the highest and lowest [Na/Fe] abundances are consistent within 1σ, while for NGC 1651, NGC 2173, and NGC 1978 the most extreme stars differ at the $\gtrsim 3\sigma$ level. There is therefore strong evidence for internal variation in [Na/Fe] in the clusters NGC 1651, NGC 2173, and NGC 1978, and ambiguous or weak evidence for NGC 1783.

The [O/Fe] abundances show considerably less variation, and it is perhaps for this reason that Mucciarelli et al. (2008) concluded that there was negligible star-to-star variation within each cluster. However, two important facts conspire to reduce the expected variation in [O/Fe] in clusters that contain second generation star formation from AGB ejecta. First, the first generation stars in the intermediate-age clusters are not α−enhanced, and so the maximum value of [O/Fe] is reduced to roughly 0.0. Second, at the moderate metallicities characteristic of these clusters, the depletion of O abundances due to hot bottom burning in AGB stars is much less than at lower metallicities characteristic of the ancient clusters. The mass- and metallicity-dependent AGB yields from the models of Ventura & D'Antona (2009) make this point clearly. In their $Z = 4 \times 10^{-3}$ models, the [O/Fe] yields for AGB stars with masses in the range $3 - 6.5$ $M_\odot$ never drop below 0.0. So while the full range in [O/Fe] for the low metallicity GCs routinely exceeds 1 dex, at higher metallicities the range is expected to collapse to nearly zero, as observed.

In Figure 5, schematic dilution models are included to guide the eye. Only NGC 1978 shows signs of a true Na-O anti-correlation. It is intriguing that this is also the most massive intermediate-age cluster in the sample. However, this is the only massive cluster studied by Milone et al. (2009) where a significant spread in its main sequence turn-off point was *not* detected, suggesting a coeval population. As noted in that work, the CMD data for this cluster were obtained in the cluster outskirts, unlike the other clusters studied. The lack of an observed age spread could therefore be explained if the second generation is more centrally concentrated than the first generation, as models predict.

While it is clear from the data that elemental abundance variations exist in the intermediate-age LMC clusters, at least for [Na/Fe], it should not be surprising if the range of the variation is smaller than in the Galactic GCs (even setting aside the previous discussion of [O/Fe]). The trend of f_p with mass found for Galactic GCs suggests that lower mass GCs are able to retain only a fraction of the AGB ejecta from first generation stars. If these LMC clusters were not dramatically more massive in their past, then the expected range in the elemental abundance variations would be smaller, as the shallower potential wells would not be able to retain as much AGB ejecta. The point is that one should not expect clusters in other environments to show the exact same abundance variations as observed in Galactic GCs. However, it *is* expected that any cluster showing an internal variation in age, as seen for these LMC clusters, should also show *some* variation in their light element abundances, as observed.

Two important conclusions emerge from this section. First, statistically-significant star-to-star scatter in the [Na/Fe] abundances exists within three of the four intermediate-age LMC clusters studied by Mucciarelli et al. (2008). This contradicts the conclusions of Mucciarelli et al., though they present no quantitative argument for a lack of star-to-star scatter. Second, a strong Na-O anti-correlation is not expected on theoretical grounds for moderate-metallicity clusters because the expected range in [O/Fe] is small. For moderate-metallicity

clusters, interpretation of any internal abundance variations must take this point into account, and it may therefore be more profitable to focus on obtaining [Na/Fe] abundances in such clusters.

5. DISCUSSION

5.1. *Origins & Implications*

The preceding analysis has revealed several important facts related to the multiple stellar population phenomenon in GCs. Perhaps most important is the result that the fraction of present day GC mass comprised of pure AGB ejecta, f_p, is large and strongly correlated with GC mass. The small scatter in f_p at fixed mass suggests that whatever process shapes the elemental abundance trends is driven primarily by internal processes, rather than external ones such as tides from the host galaxy. It is puzzling why f_p is so strongly correlated with mass and yet such a weak function of mass (varying by less than a factor of two over two decades in GC mass).

There are at least two possible explanations for the observed correlation between f_p and GC mass. First, the amount of AGB material retained within a GC may decrease with decreasing GC mass. This is plausible, as lower mass GCs have lower escape velocities, and yet the typical velocity of AGB ejecta is independent of GC mass. A second possibility is that GCs retain all of their AGB ejecta but this material is more strongly diluted by pristine material accreted from the ambient ISM in lower mass GCs. Lower mass GCs could more efficiently accrete pristine material if ISM sweeping is the dominant mechanism bringing in new material (Conroy & Spergel 2011). The former explanation seems more natural and is therefore preferred.

The derived fraction of mass in second generation stars presents one of the most significant outstanding puzzles. It is observed to be $> 50\%$ of the total present GC mass and is relatively independent of mass. This fraction is derived in the present work, but has been found also by many authors through different techniques (e.g., Smith 1987; Carretta et al. 2010c). If GCs were > 10 times larger at birth, then the early contribution of second generation stars to the total was small, of order a few percent. The fact that present day GCs always end up with roughly the same fraction of second generation stars strongly suggests that there is some mechanism that drives all clusters toward this state. One scenario that could achieve this is as follows. Imagine that some mechanism causes the first stellar generation to become unbound on the same timescale as the formation of the second generation (see below for an example). The second generation, being more tightly bound, would remain so, and might also be capable of capturing of order its own mass in first generation stars.

The second major outstanding puzzle is the more fundamental issue of how and why the ancient GCs were initially so much more massive at birth. Standard dynamical effects cannot explain this, essentially because the relaxation time increases with increasing mass, and yet the mass enhancement factors are larger at higher masses. The only somewhat plausible scenario that has been proposed to explain this is *primordial* mass segregation of the stars in the first stellar generation (e.g., D'Ercole et al. 2008). If a significant fraction of high mass stars were born near the cluster center, then as they evolve and die they will carry away a significant fraction of the total binding energy of the young GC, causing it to expand significantly. There is some circum-

stantial evidence for primordial mass segregation in nearby young clusters whose ages are comparable to their crossing times (e.g., Hillenbrand & Hartmann 1998; de Grijs et al. 2002; Stolte et al. 2006; Gennaro et al. 2011).

If primordial mass segregation were strong enough, it could unbind young GCs on a timescale of $\lesssim 1$ Gyr (Vesperini et al. 2009), or at least lead to a substantial amount mass loss and cluster expansion (Marks & Kroupa 2010). If this were a common feature of GC evolution, then perhaps GCs owe their very survival to the formation of tightly bound second generation stars (D'Antona & Ventura 2008). These second generation stars, born at the bottom of a deep potential well set by the first generation stars, should be relatively immune to the effects of primordial mass segregation. Detailed simulations will be required to validate this scenario, of which the simulations by (D'Ercole et al. 2008) are an important first step. If confirmed, this would constitute a major revision to our understanding of the survival of massive star clusters.

A novel implication of the fact that the ancient GCs were much more massive at birth is their potential contribution to the Galactic stellar halo (see also Vesperini et al. 2010; Schaerer & Charbonnel 2011). There are currently ≈ 150 known GCs (Harris 1996), and they have an average present mass of $10^{5.5}$ $M_\odot$. If these GCs had on average 10 times more long-lived stars at birth, then in total they would have equaled a mass of $\approx 5 \times 10^8$ $M_\odot$. This value is within a factor of a few of the estimated stellar mass of the Galactic stellar halo (e.g., Siegel et al. 2002), and of the stellar halo in M31 (e.g., Kalirai et al. 2006). This is the contribution to the stellar halo of GCs that remain bound at the present epoch. Martell & Grebel (2010) have shown that approximately half of the Milky Way (MW) stellar halo could have formed from GCs that are now disrupted. An understanding of the early evolution of GCs may therefore be required in order to understand the hierarchical formation of the stellar halos around galaxies.

If the average GC today was 20 times more massive at birth, then it would have had a mass of $\approx 6 \times 10^6$ $M_\odot$, and it would have formed out of a giant molecular cloud (GMC) with a mass of at least $\sim 10^7$ $M_\odot$, assuming $\epsilon_{\rm SF} = 0.5$. Such large GMCs should form in the massive, gas-rich protogalactic disks common at high redshift (Escala & Larson 2008). Indeed, observations of disk-dominated galaxies at $z \sim 2$ have identified large numbers of super-star forming clumps with masses of order 10^9 $M_\odot$ (Genzel et al. 2008). Each of these clumps could easily spawn several massive young GCs. Even at the present epoch young clusters have been found with dynamical masses in excess of 10^7 $M_\odot$ (e.g., Maraston et al. 2004; Bastian et al. 2006). While rare at the present epoch, the conditions at high redshift may well have favored the formation of many such massive objects.

M31 contains a large number of extended, low surface brightness GCs with half-light radii > 10 pc (Huxor et al. 2005) that have no counterparts in the Galaxy. The origin of these extended GCs is not known. In the context of the present discussion, they could arise from the rapid expansion caused by primordial mass segregation. If for some reason these clusters formed in a much more benign tidal field than the GCs in the Galaxy, then the loosely bound stars may not have been stripped by the present epoch. If this scenario is correct, then these extended GCs are comprised principally of first generation stars, and should contain a small core of second generation stars at their center. Radial gradients of the

CN absorption feature in these GCs would be very interesting.

The conclusion that GCs were much more massive in the past may also require some revision to dynamical models for the long-term evolution of the GC population (Gnedin & Ostriker 1997; Fall & Zhang 2001; Marks & Kroupa 2010).

While the present analysis provides a self-consistent explanation for the variation in the extent of the Na-O anti-correlation from cluster to cluster, complications arise when considering other light elements. In particular, some clusters that show an Na-O anti-correlation do not harbor a corresponding Mg-Al anti-correlation (Carretta et al. 2009b). For example, the clusters NGC 6121 and NGC 6752 have very similar [Fe/H], total mass, and f_p parameters, and yet the former shows no star-to-star variation in either Mg or Al, while the latter shows clear variations in both. The Mg and Al yields depend on AGB mass in a manner different from the Na and O yields (Ventura & D'Antona 2008b), and so it is possible that differences in Mg-Al anti-correlations in GCs that contain the same Na-O anti-correlation arise from a difference in the average AGB mass that donates ejecta for later star formation. See Carretta et al. (2009b) for further discussion.

5.2. *Alternative Explanations*

A number of alternative explanations have been proposed for various aspects of the standard model considered herein. Several of these will be briefly discussed in this section; the reader is referred to Renzini (2008) and Conroy & Spergel (2011) for further discussion.

While AGB ejecta is the favored source for the processed material, other proposed sources include winds from massive ($\gtrsim 20$ $M_\odot$) rotating stars (Decressin et al. 2007b) and massive binary star interactions (de Mink et al. 2009). The most serious objection to these scenarios is that they are associated with massive stars with short lifetimes. It is therefore not natural for the processed material to remain free of supernovae contamination. For example, it is not obvious why the second stellar generation should have the same [Ca/Fe] abundances as the first generation in these scenarios, and yet this is observed to be so (Carretta et al. 2010b).

The similar 10^8 yr timescales for both intermediate-mass AGB stars and the drop in UV photons from the first generation provide a simple framework to understand not only the ancient GCs but also the observed age spread within intermediate-age LMC clusters. Invoking processed material from massive stars requires either a more nuanced or an altogether different mechanism to be at work in the LMC clusters compared to ancient GCs. This seems unappealing on the principle of simplicity.

Several authors have considered the possibility that stars with anomalous abundance ratios simply had their surfaces polluted by AGB ejecta (e.g., D'Antona et al. 1983; Thoul et al. 2002). In this scenario there is only one generation of star formation and the observed range in light element abundances is due to the differing amount of surface pollution from star to star. A major advantage of this scenario is that the GCs need not have been substantially more massive at birth because a much smaller amount of AGB ejecta is needed to cover the surfaces of stars.

This scenario is almost certainly ruled out by the lack of strong [O/Fe] and [Na/Fe] abundance variations between the main sequence and red giant branch (RGB). A 1 $M_\odot$ star on the RGB has a convective envelope comprising approximately 40% of its mass, while the same star on the main se-

quence has a negligible convective envelope. Therefore, this model would predict that as such a star evolves from the main sequence onto the RGB, surface pollution would be heavily diluted as the convective envelope deepens. This is not observed, which either means that the scenario is to be discounted (as suggested in Cohen et al. 2002), or the amount of surface pollution was substantial, so that it could not be diluted even by deep convection. The latter possibility then requires large amount of AGB ejecta, which means that large mass enhancement factors are required.

Recently, Conroy & Spergel (2011) proposed a scenario for the formation of multiple stellar populations within GCs that contains many of the ingredients listed in the Introduction, e.g., AGB ejecta and matter accreted from the ambient ISM as the source of second generation stars. The principle difference between that model and the D'Ercole et al. (2008) model is that the former explicitly attempted to avoid the conclusion that the ancient GCs were much more massive at birth. Instead, the large amount of material needed to form the second generation stars came primarily from the ambient ISM. As found in previous work and confirmed herein (see also D'Ercole et al. 2011), the difficulty with such a scenario in explaining the properties of the ancient MW GCs is that too few anomalous stars are produced. This is because the accreted ambient ISM, which has normal abundance patterns, dominates the mass budget. This does not preclude the possibility that star clusters in other systems formed a second generation of stars from primarily accreted ambient ISM material.

Finally, several related scenarios appeal to highly unusual stellar configurations in order to explain the high number of anomalous stars (e.g., Bekki 2006; Bekki et al. 2007; Marcolini et al. 2009). These scenarios have two important properties in common. First, due to the special configurations required, they cannot be expected to operate at the present epoch, and therefore the multiple stellar population phenomenon observed in intermediate-age LMC clusters requires a second, distinct explanation. Second, they do not require present day GCs to have been substantially more massive at birth.

The scenario outlined by Bekki (2006), for example, envisions GC formation at the centers of their own dark matter halos. Stars throughout the dark halo are allowed to donate their AGB ejecta to the central regions where the GC is expected to form. Unfortunately, a number of indirect arguments disfavor GC formation at the centers of their own dark halos (see, e.g., Conroy & Spergel 2011, for a review), and direct dynamical searches for dark halos around present day isolated GCs strongly disfavor the presence of dark halos (Baumgardt et al. 2009; Conroy et al. 2011). Since the deep potential well provided by a dark halo should efficiently retain supernovae ejecta, it is also not clear why GCs in this scenario should not all have large internal variation in heavier elements such as Fe and Ca.

6. SUMMARY

A simple model has been presented to interpret the observed Na-O anti-correlation in 20 Galactic GCs. The model assumes that GCs are composed of two generations of stars: a first generation formed from material with abundance ratios characteristic of field stars, and a second generation formed from a mix of AGB ejecta from the first generation and material accreted from the ambient ISM. Principal results from this analysis include the following:

- The fraction of present GC stellar mass comprised of AGB ejecta is strongly correlated with GC mass, varying from 0.2 to 0.45 over a factor of 100 in GC mass. This result is grounded in the observation that the extent of the observed Na-O anti-correlation is strongly correlated with GC mass.

- The fraction of GC mass in pure AGB ejecta, in conjunction with several well-motivated assumptions, provides strong constraints on the composition and mass-loss history of Galactic GCs. The fraction of mass contained in second generation stars is always greater than 50%, for GCs ranging in mass between $10^{4.5}$ $M_\odot$ and $10^{6.5}$ $M_\odot$. The population of first generation stars in GCs must have been factors of $20-60$ larger at birth compared to the present epoch. However, owing to the fact that first generation stars are subdominant at the present epoch, the total GC mass was only factors of $10-20$ larger at birth. These factors are mass-dependent and lower limits. The ancient GCs were therefore much more massive at birth.

- Elemental abundance data on four intermediate-age ($1-2$ Gyr) LMC clusters are reinterpreted in the context of the models presented herein. It is found that three of the four clusters show unambiguous evidence for internal variation in [Na/Fe] abundances. [O/Fe] values do not show signs of star-to-star variation, but this is shown to be a natural expectation in moderate metallicity clusters. The scenario invoked to explain the properties of the ancient Galactic GCs therefore appears to also be at work at the present epoch in the LMC.

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